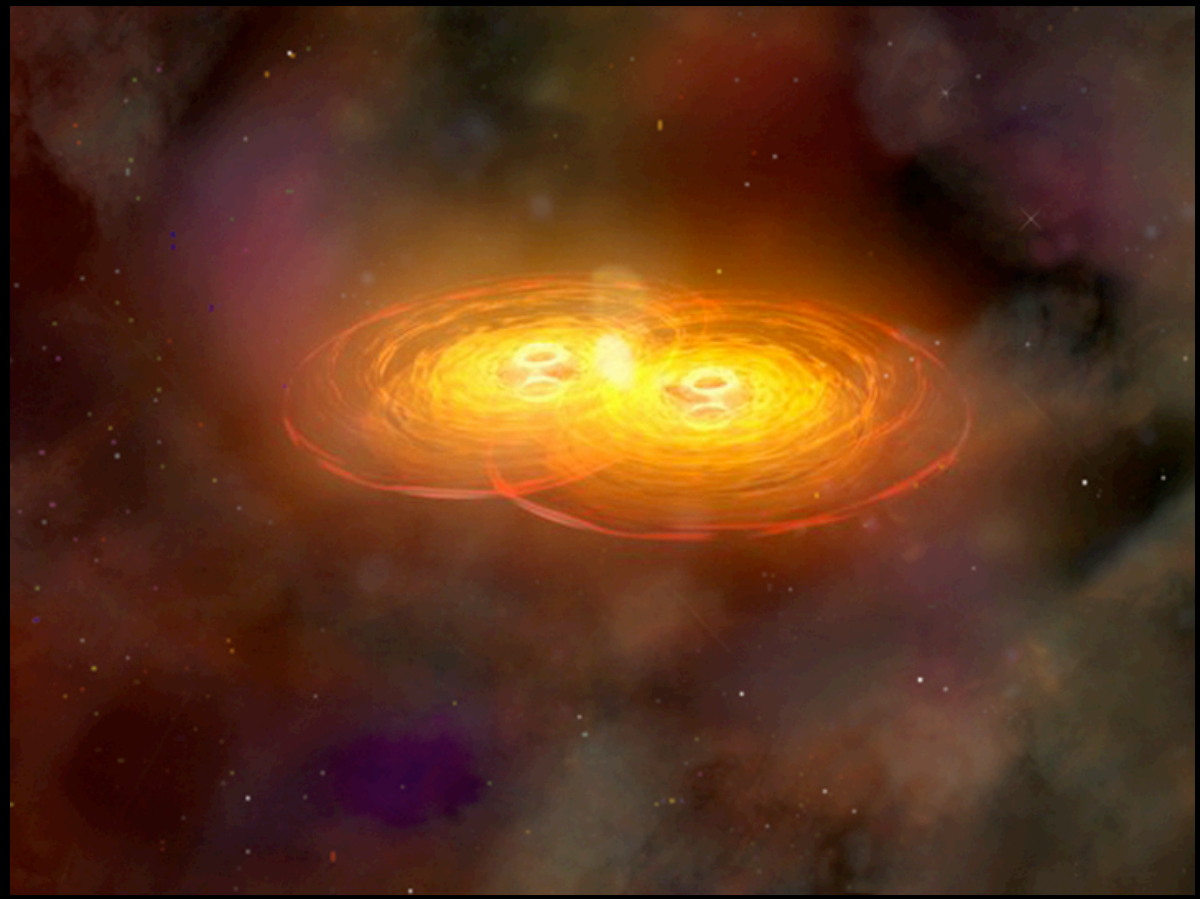
The interplay of black hole binaries with their environment in gas-rich mergers

Marta Volonteri

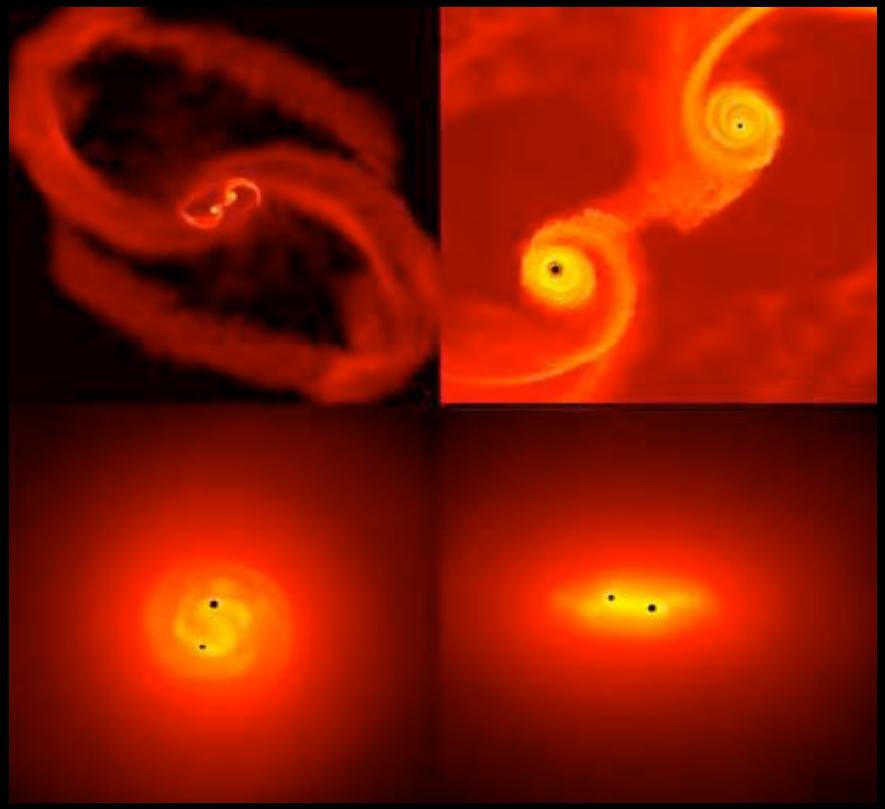
University of Michigan

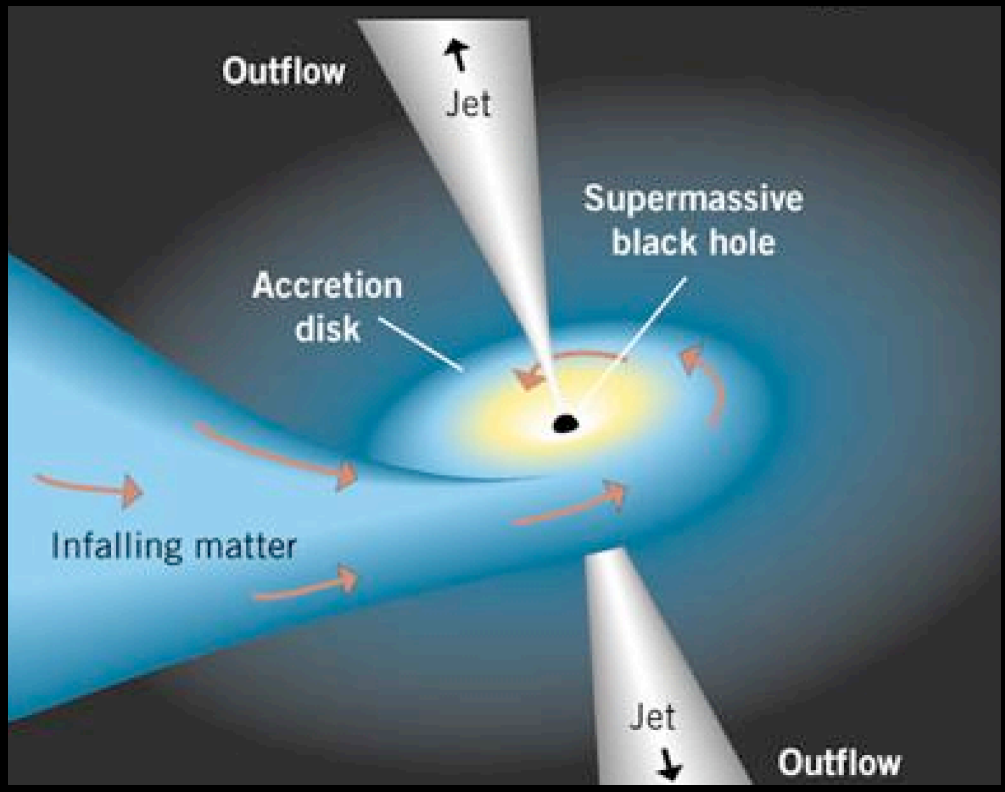


Hierarchical evolution of MBHs

How do MBHs grow to become supermassive?

BH-BH mergers and gas accretion





What we want to know

- How and when BHs accrete mass
- How fast BHs spin
- How and when BHs merge

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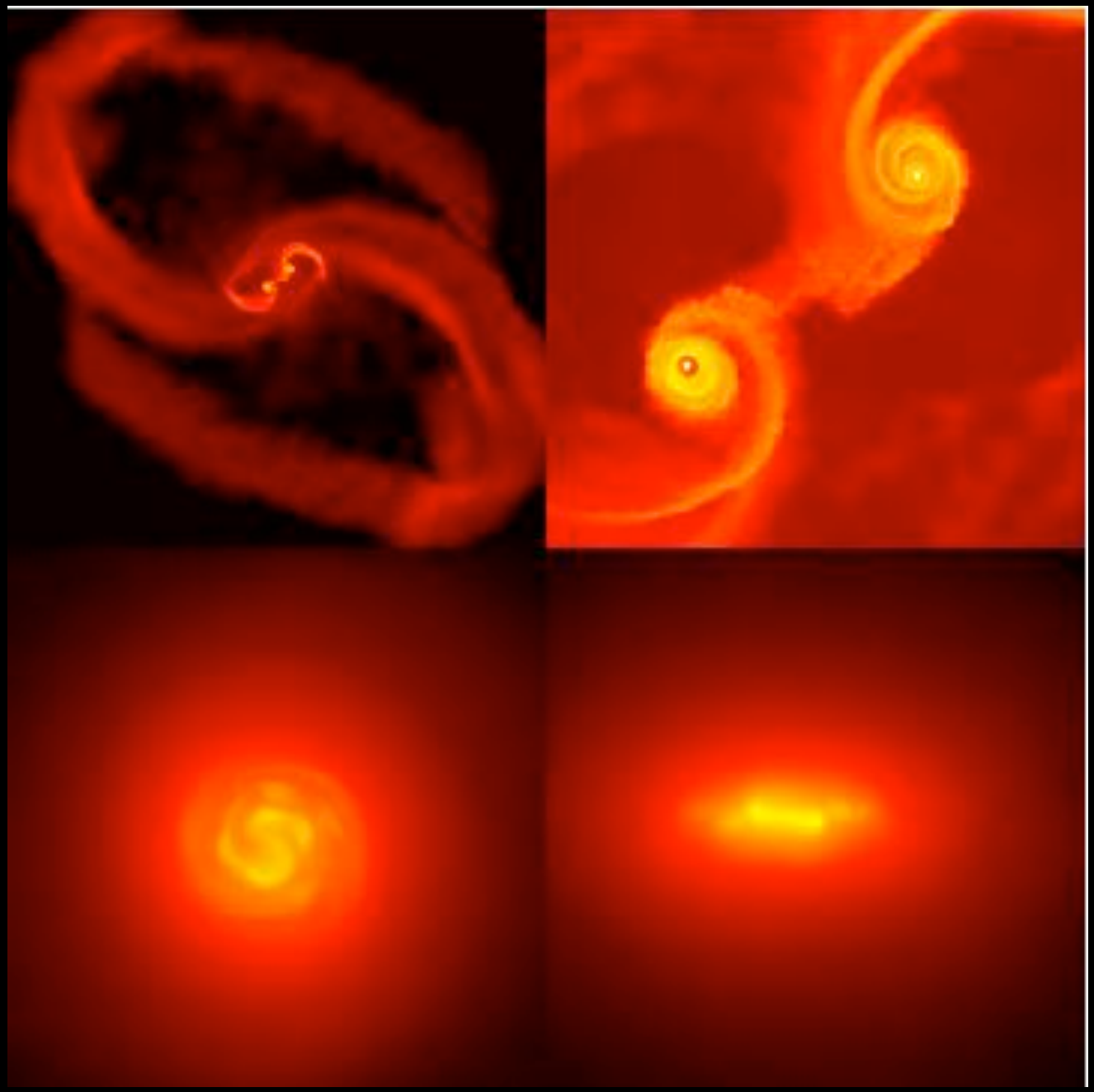
Mergers and accretion

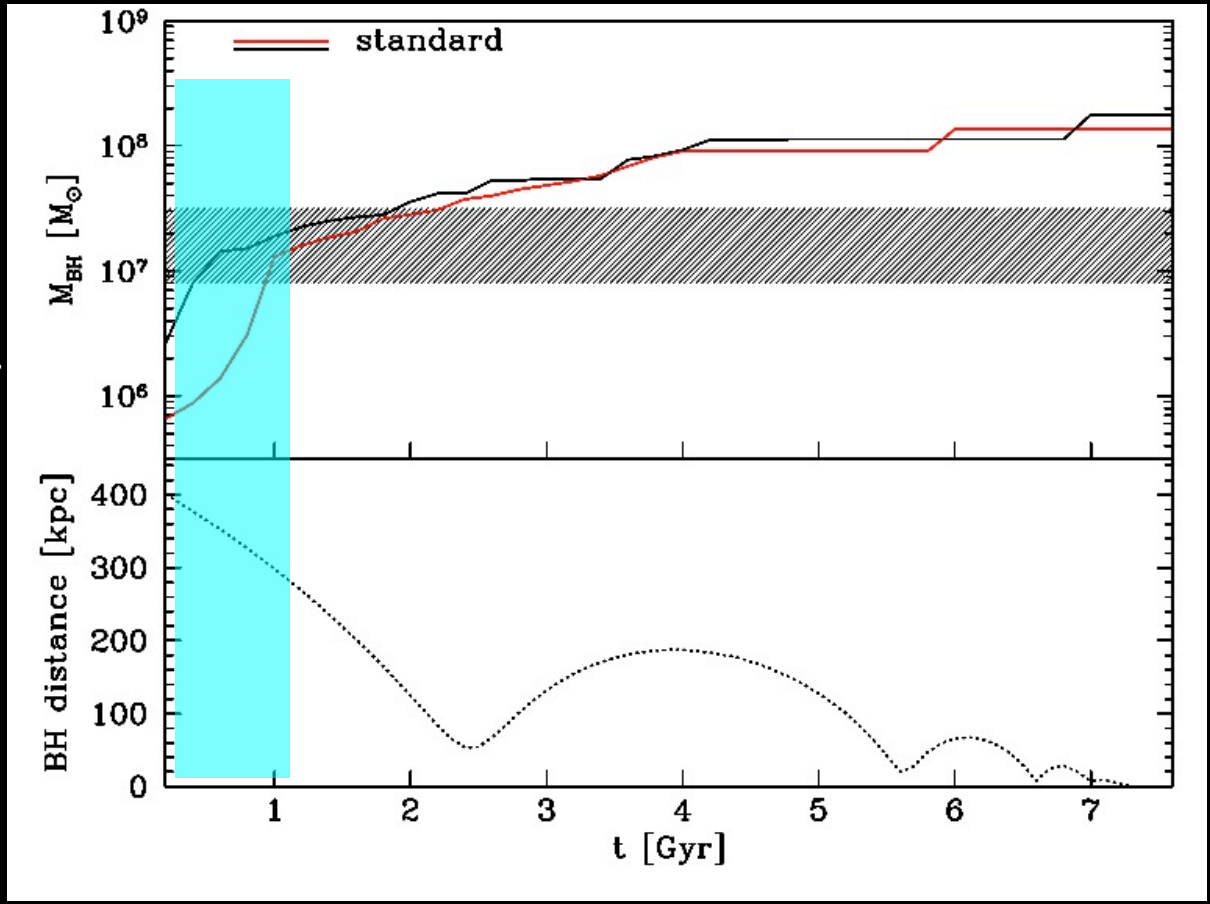


Do MBHs accrete
before
or
after
merging?

Katzantidis et al.,
Mayer et al., di Matteo et al.,
Hopkins et al.

Merger driven accretion

courtesy of S. Callegari

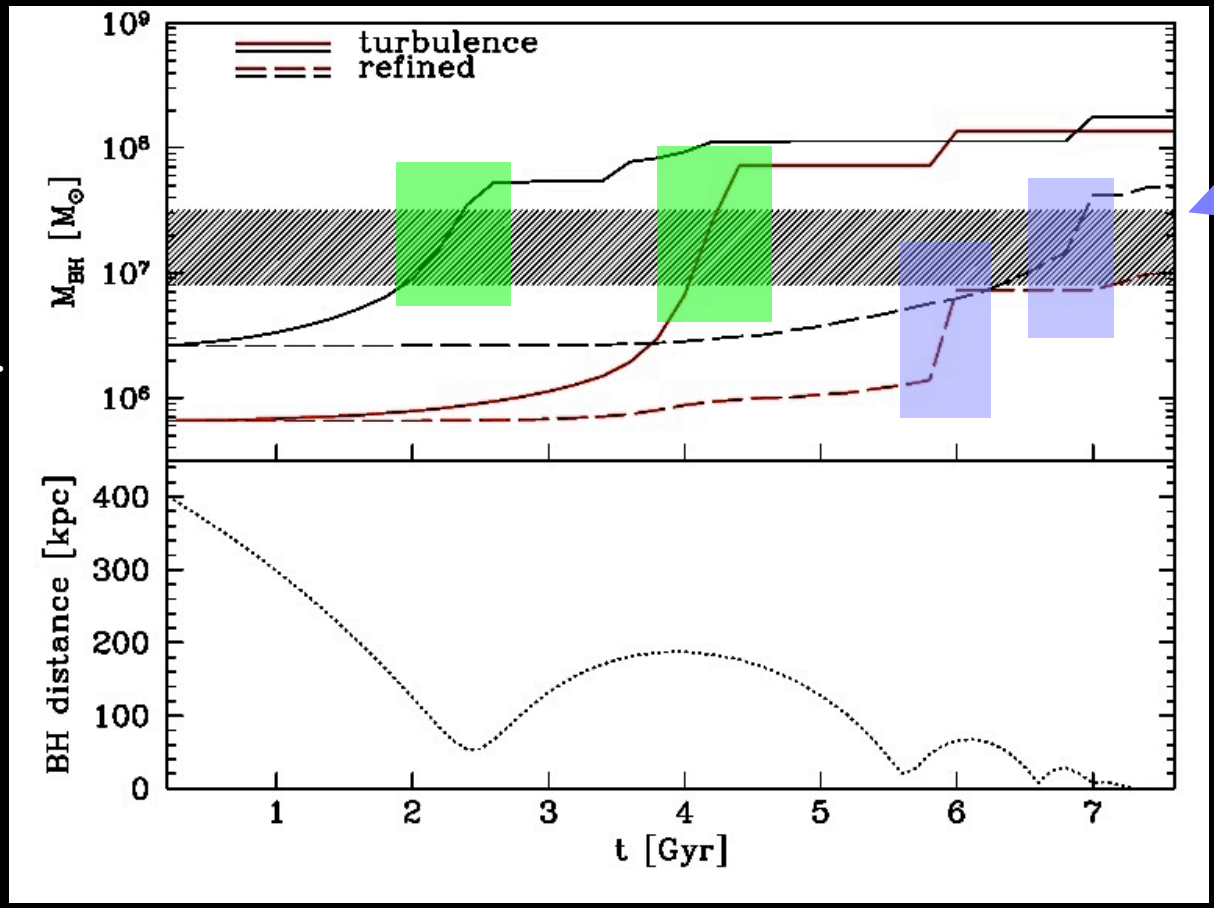


-"Standard" numerical Bondi-Hoyle accretion

-No feedback

Merger driven accretion

courtesy of S. Callegari



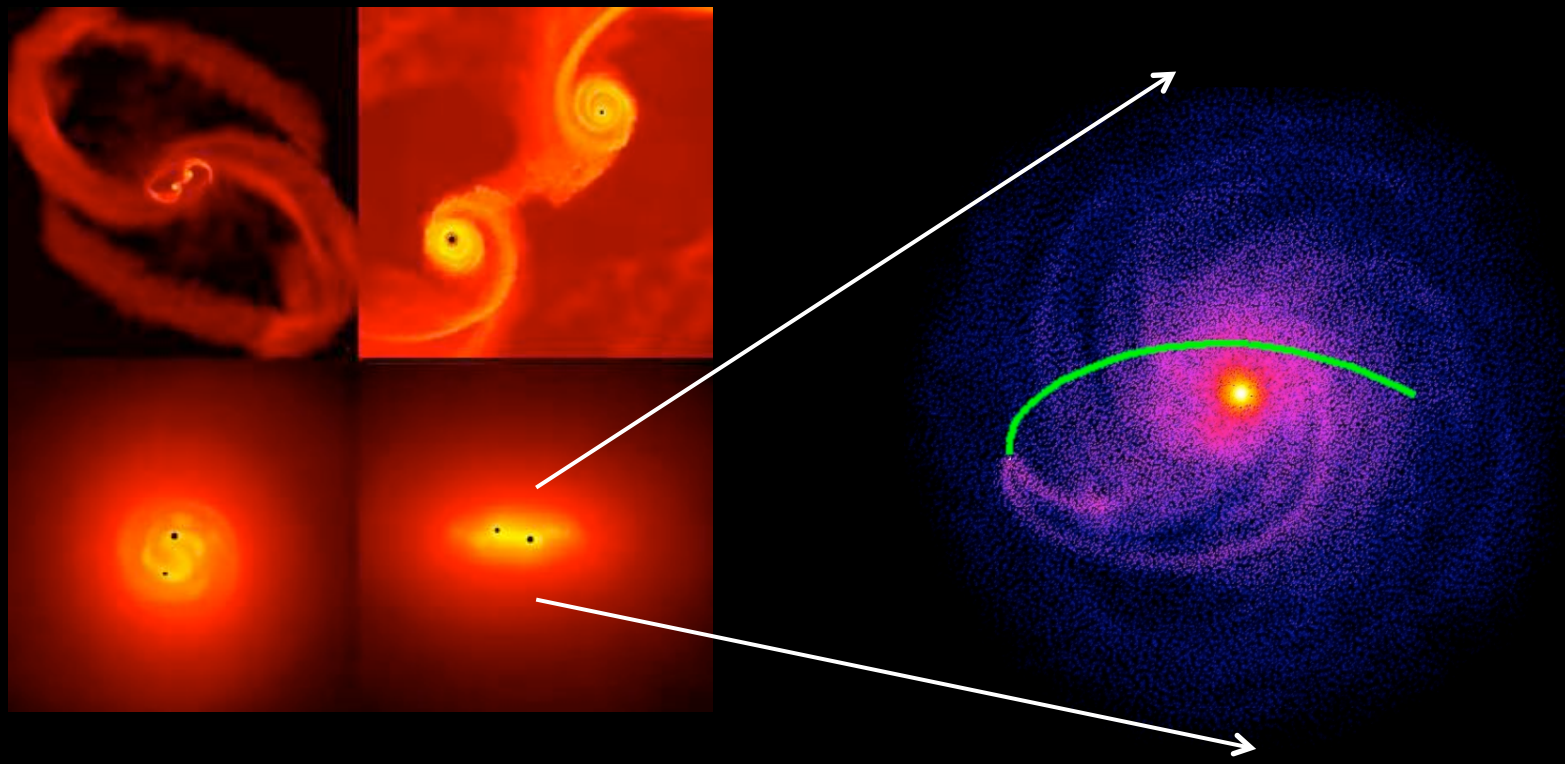
High resolution simulations: M-σ without feedback

- **turbulent motions**

- **extrapolation from the refined simulation**

MBHs in merger remnants

Dotti et al. 2009



MBHs in circumnuclear disks

Dotti et al. 2009

Central MBH:
$M_{BH} = 4 \times 10^6\ M\odot$

Gaseous disk (Mestel):
$M_{Disc} = 10^8\ M\odot$

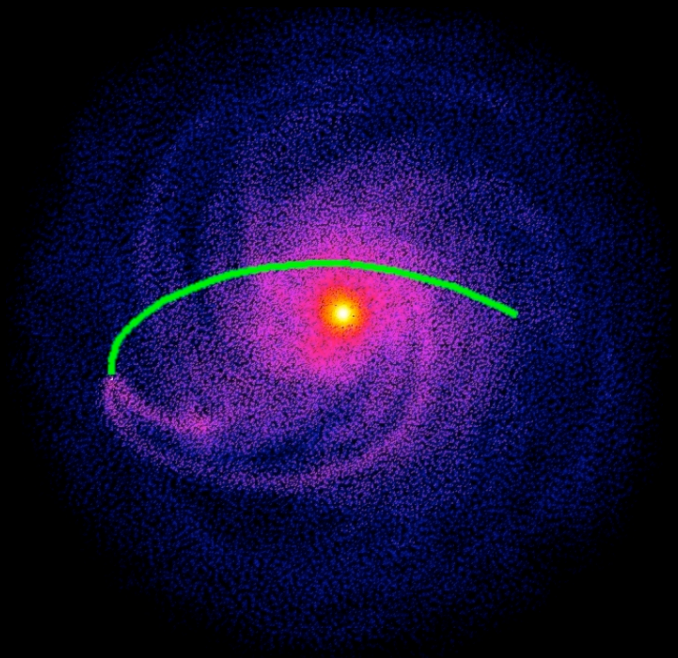
$R_{Disc} = 100$ pc

Stellar bulge (Plummer):

$M_{Bulge} = 7 \cdot 10^8\ M\odot$

$a = 55$ pc

Secondary MBH:
$M_{BH} = 4 \times 10^6\ M\odot$
e ≈ 0.7
co- or counter- rotating



MBHs in circumnuclear disks

Dotti et al. 2009

Adiabatic evolution:

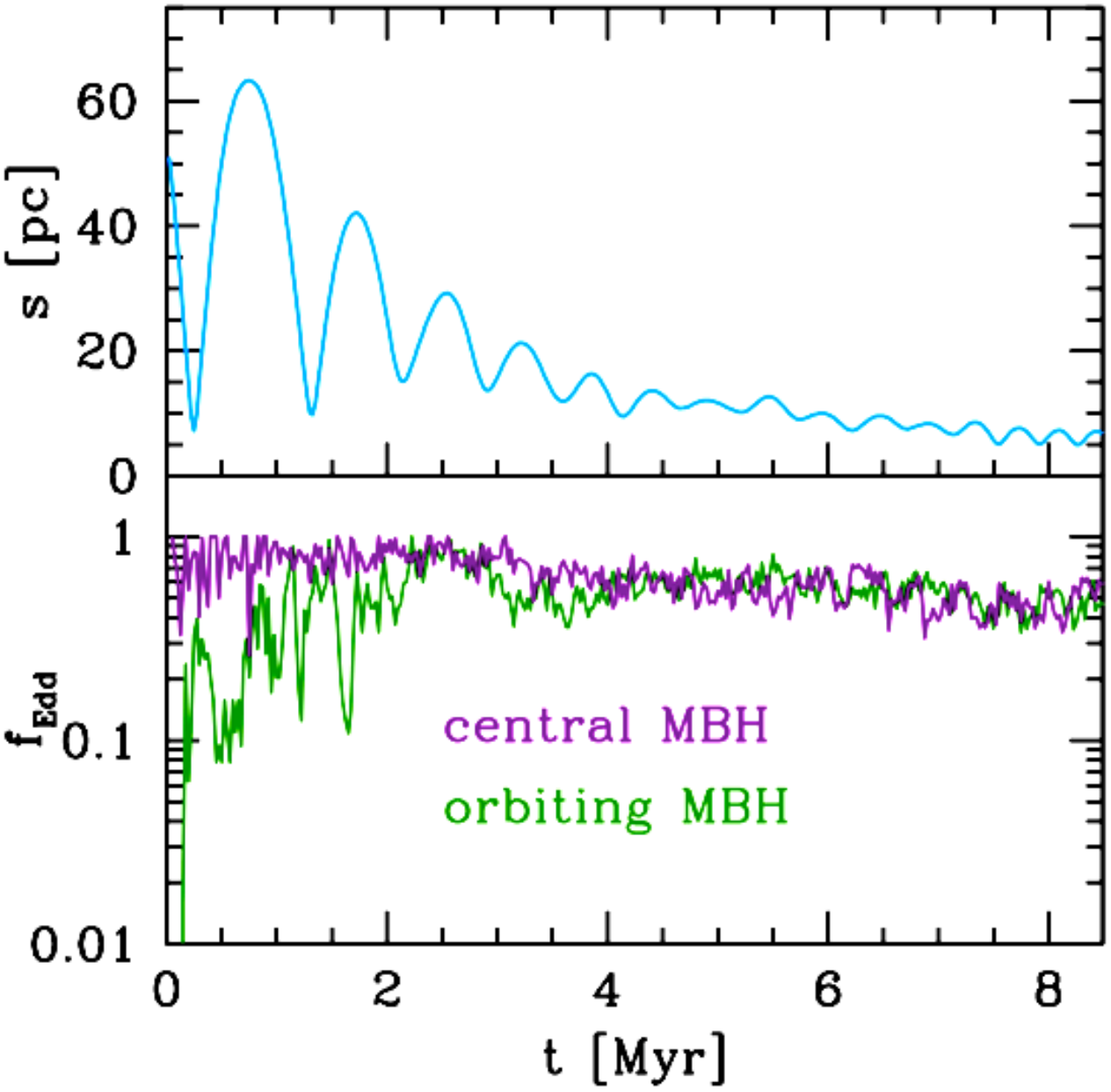
'COLD' disk: $\gamma=7/5$

'HOT' disk: $\gamma=5/3$

Accretion:

- accrete only bound particles, within Bondi radius
- need to resolve the MBHs Bondi radii (h=0.1 pc)

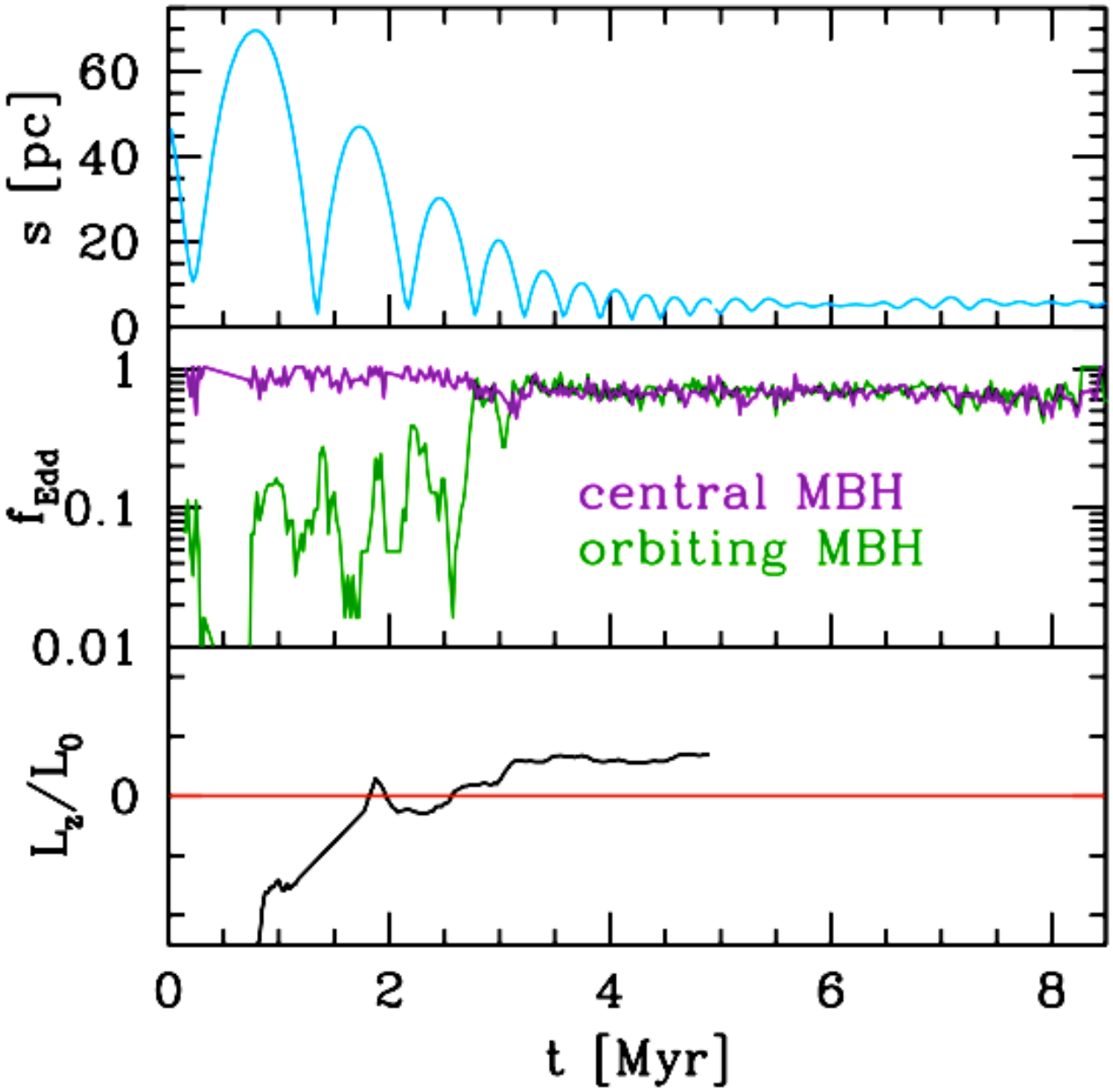
Co-rotating MBH (γ=5/3)



Modulation in the accretion rate of the orbiting MBH

Accretion rate depends on the relative velocity between MBH and gas

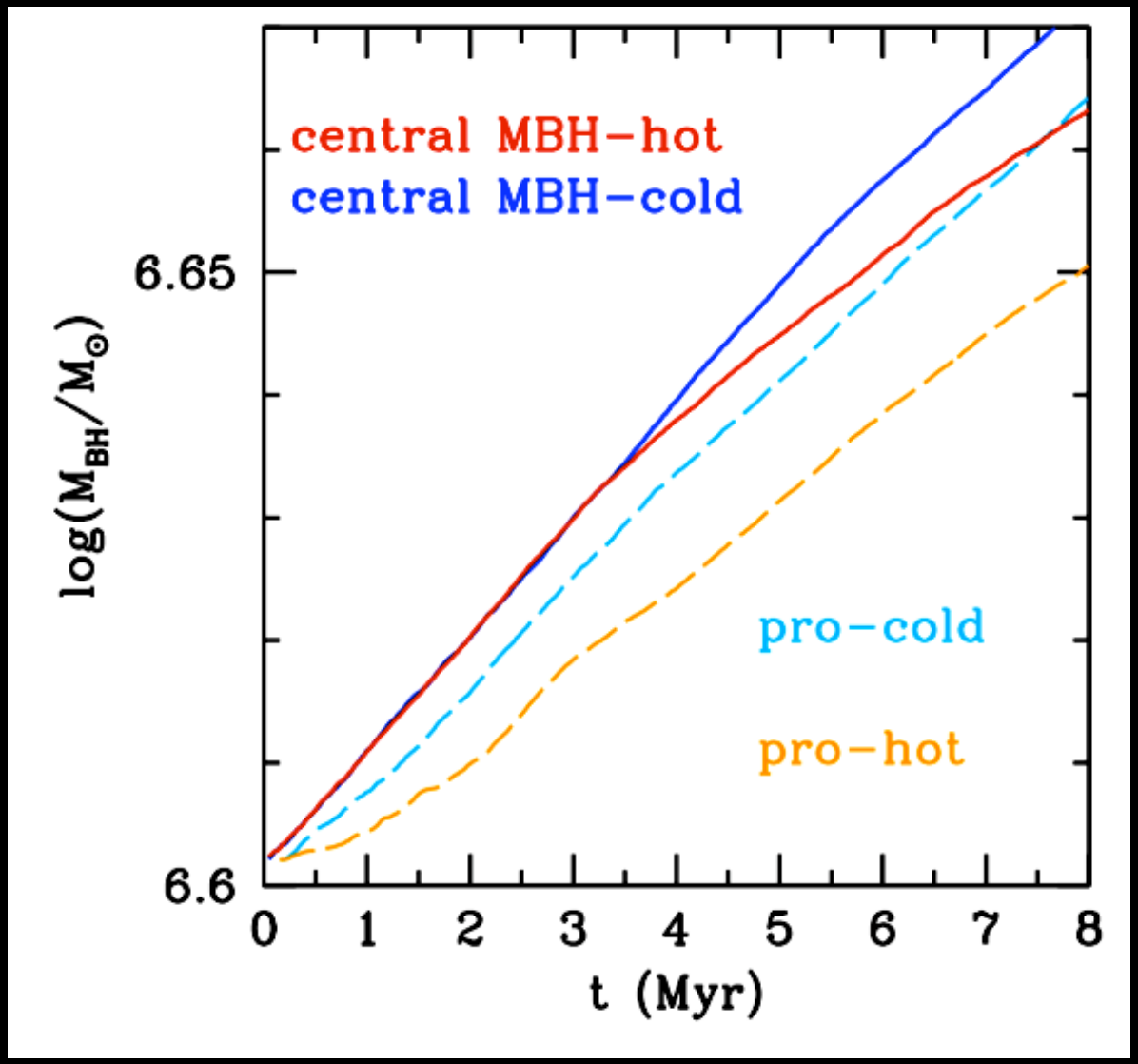
Counter-rotating MBH (γ=5/3)



Accretion rate depends on the relative velocity between MBH and gas

Accretion rate jumps when the MBH starts co-rotating – angular momentum flip

MBH mass accretion



Accretion depends on the **orbital evolution**

Accretion depends on the **thermodynamical** properties of the gas

What we want to know

- How and when BHs accrete mass
- How fast BHs spin
- How and when BHs merge

The second hair: spins

- ✔ maximal accretion efficiency

  Schwarzschild: spin=0 ε=0.06

  maximally rotating: spin=0.998 ε=0.31

- ✔ growth time $$t_{acc} = 0.45 \frac{\epsilon}{1-\epsilon} \ln(\frac{M_{fin}}{M_{in}}) \mathrm{Gyr}$$

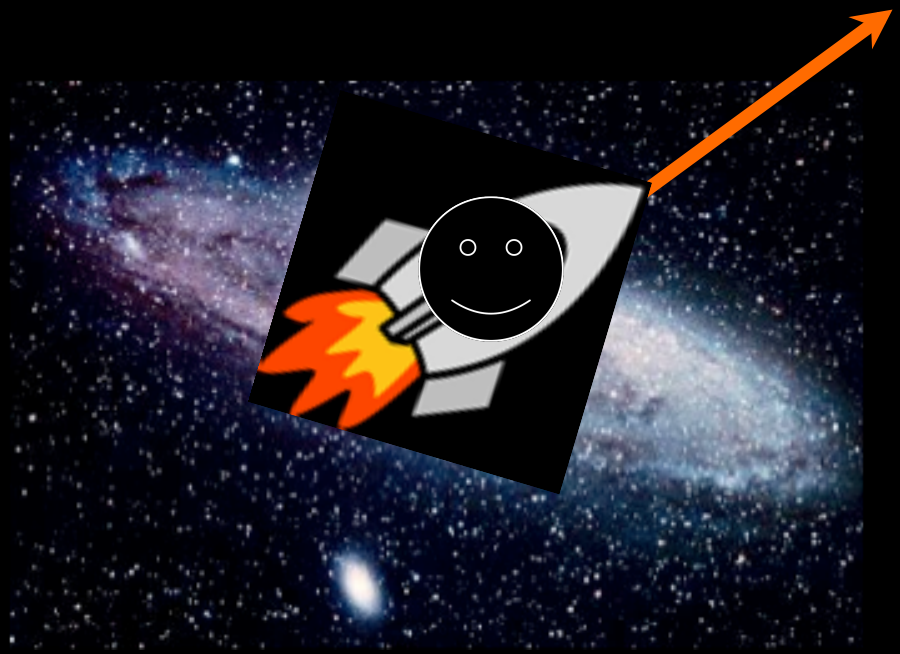
- ✔ importance of Blandford-Znajek energy extraction

- ✔ GW parameters estimates

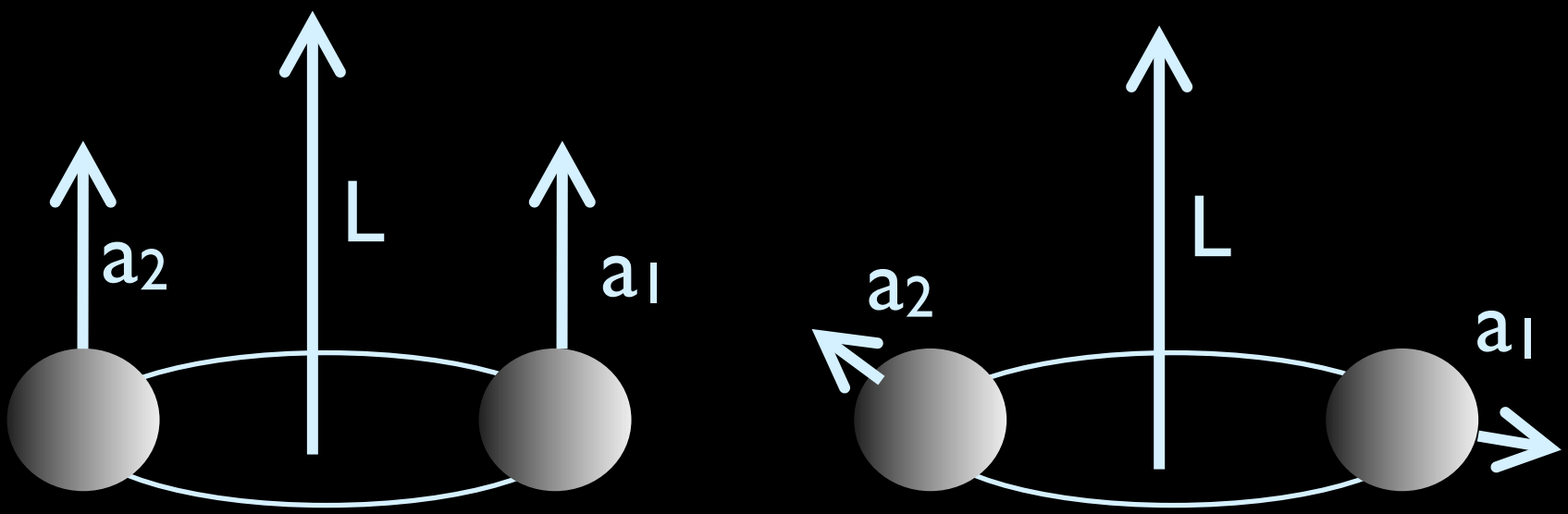
- ✔ recoil velocities

Gravitational recoil

binary center of mass recoil during coalescence due to asymmetric emission of GW

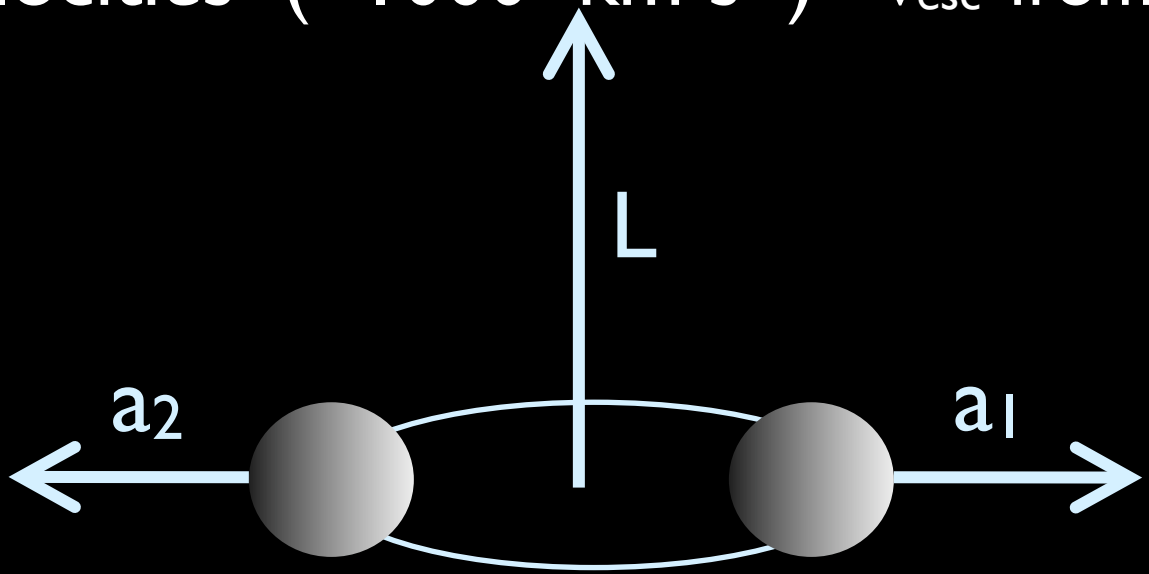


Recoiling MBHs



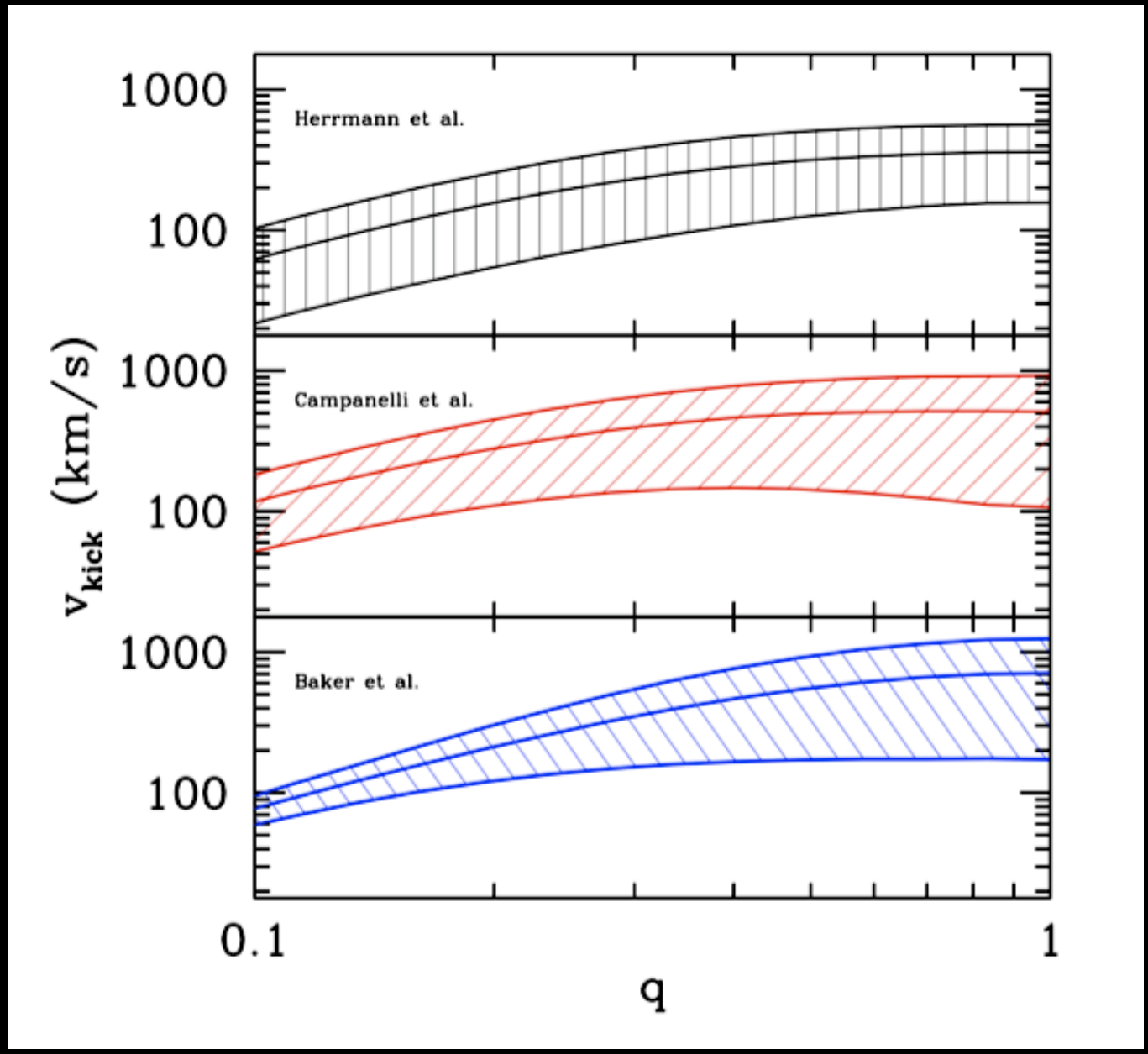
Low kick velocities (~100 km s^{-1}) ~v_{esc} from high-z galaxies

High kick velocities (~1000 km s^{-1}) ~v_{esc} from today's galaxies



500.000 MC realizations for each $q=m_2/m_1$:

- |a| homogeneously distributed between 0 and 1
- directions isotropically distributed



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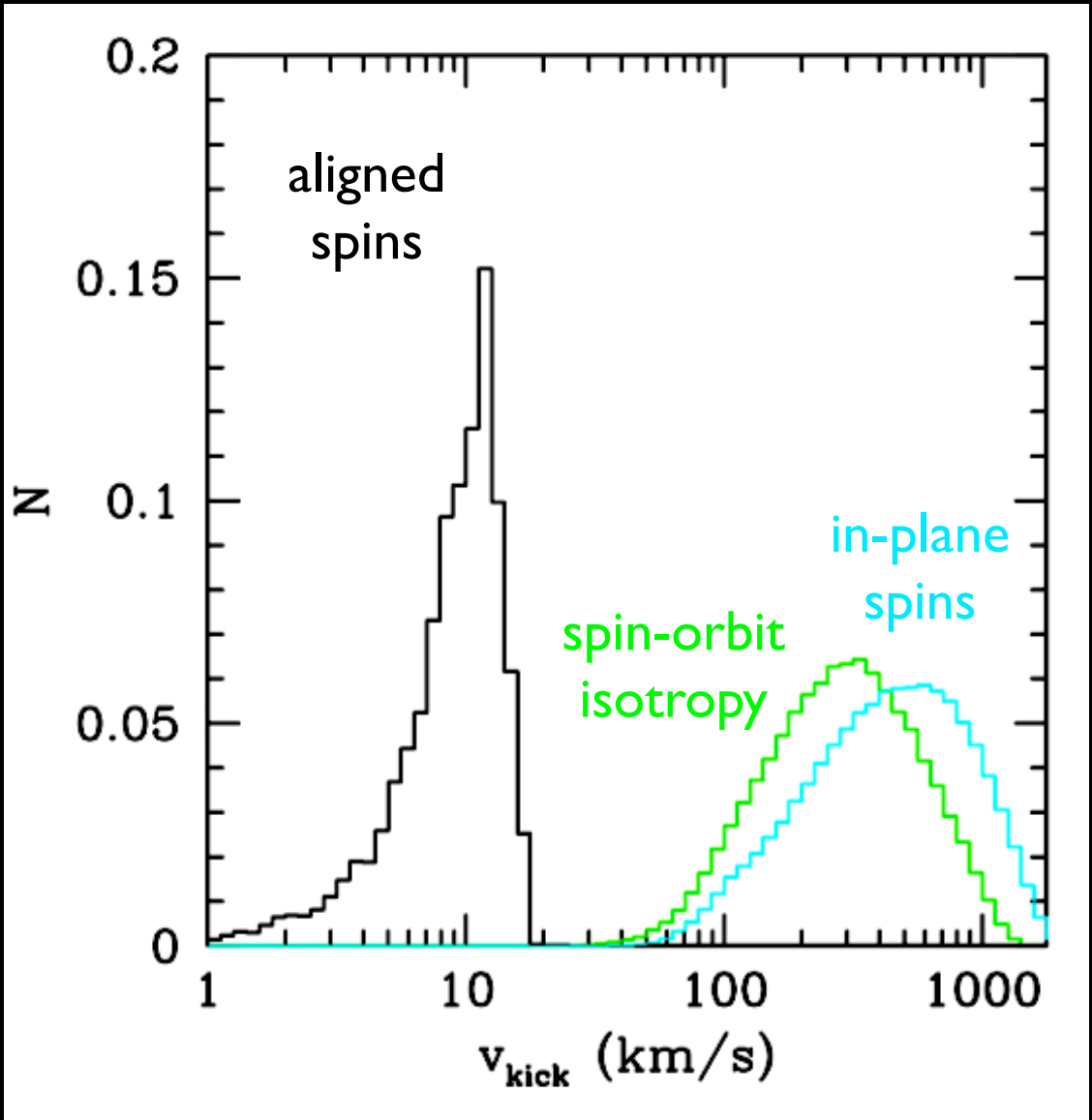


Random distribution of spin moduli

MBH mass ratio directly from the simulations: $q=m_2/m_1 \sim 1$

Dotti,MV et al. 2009

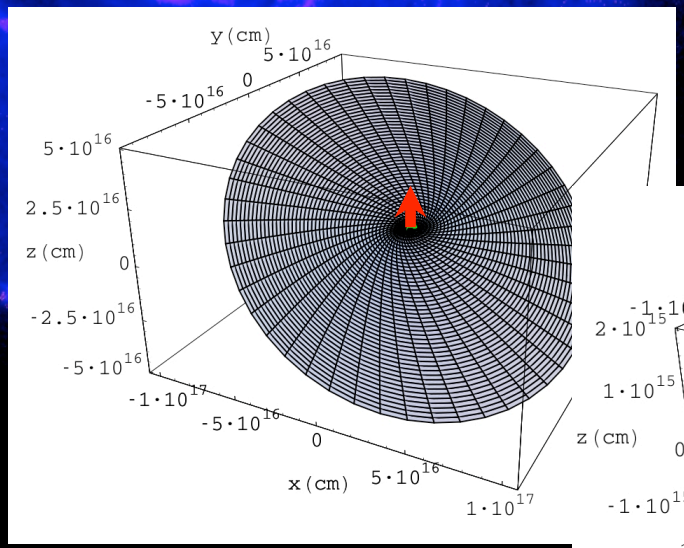
Spin evolution

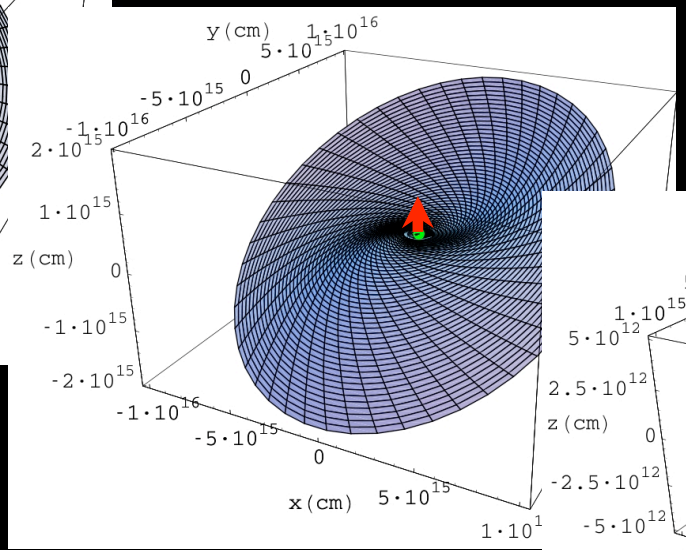
Simulations { accretion rate

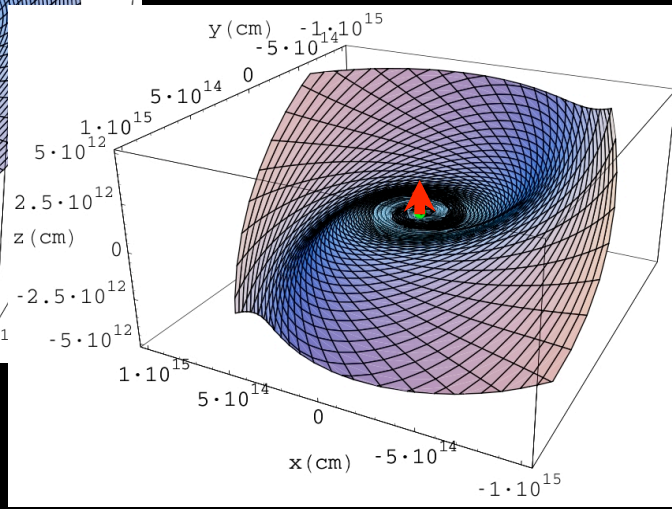
ang. mom. accreting flow

Bardeen-Peterson effect → BH- SS disc alignment

Perego, . . , MV 2009







Perego,..., MV 2009

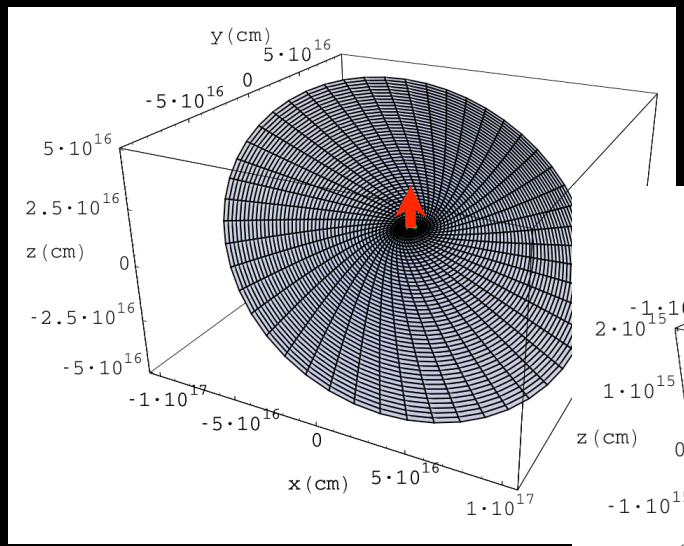
Spin evolution: Bardeen-Peterson effect

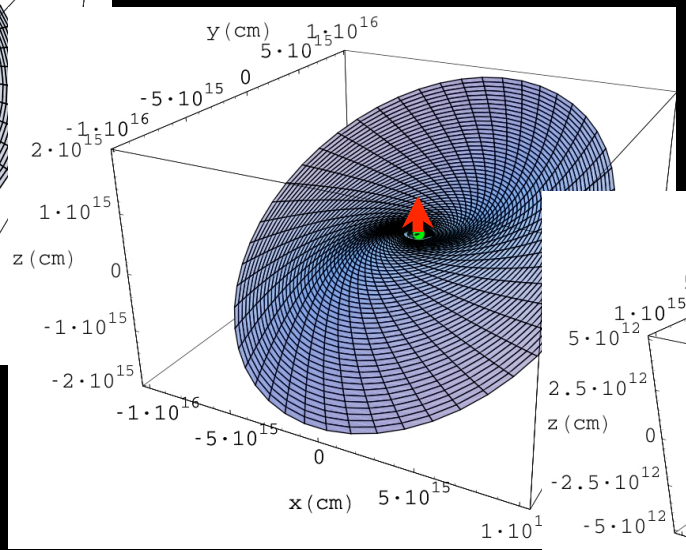
$$\frac{d\mathbf{J}_{\rm BH}}{dt} = \dot{M}\Lambda(R_{\rm ISO})\hat{\mathbf{l}}(R_{\rm ISO}) + \frac{4\pi G}{c^2}\int_{\rm disc}\frac{\mathbf{L}(R)\times\mathbf{J}_{\rm BH}}{R^2}dR.$$

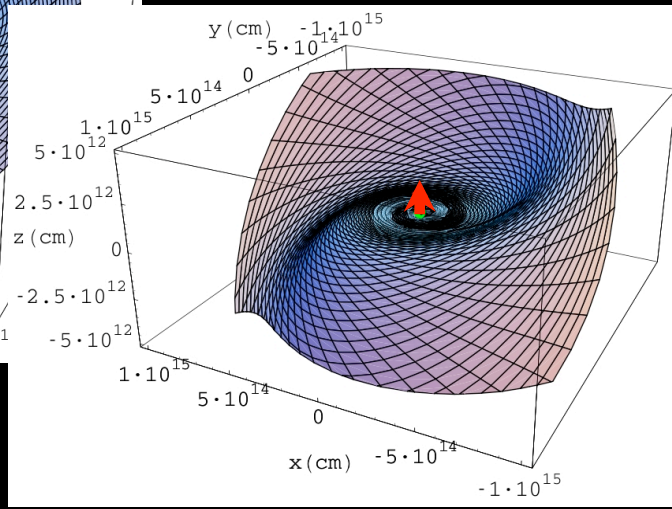
$$\left|\frac{4\pi G}{c^2}\int_{\rm disc}\frac{\mathbf{L}(R)\times\mathbf{J}_{\rm BH}}{R^2}dR\right| \sim \frac{4\pi G}{c^2}\frac{L(R_{\rm warp})J_{\rm BH}\sin\theta_{\rm out,0}}{R_{\rm warp}}$$

$$R_{\rm warp} = \frac{4GJ_{\rm BH}}{\nu_2 c^2}.$$

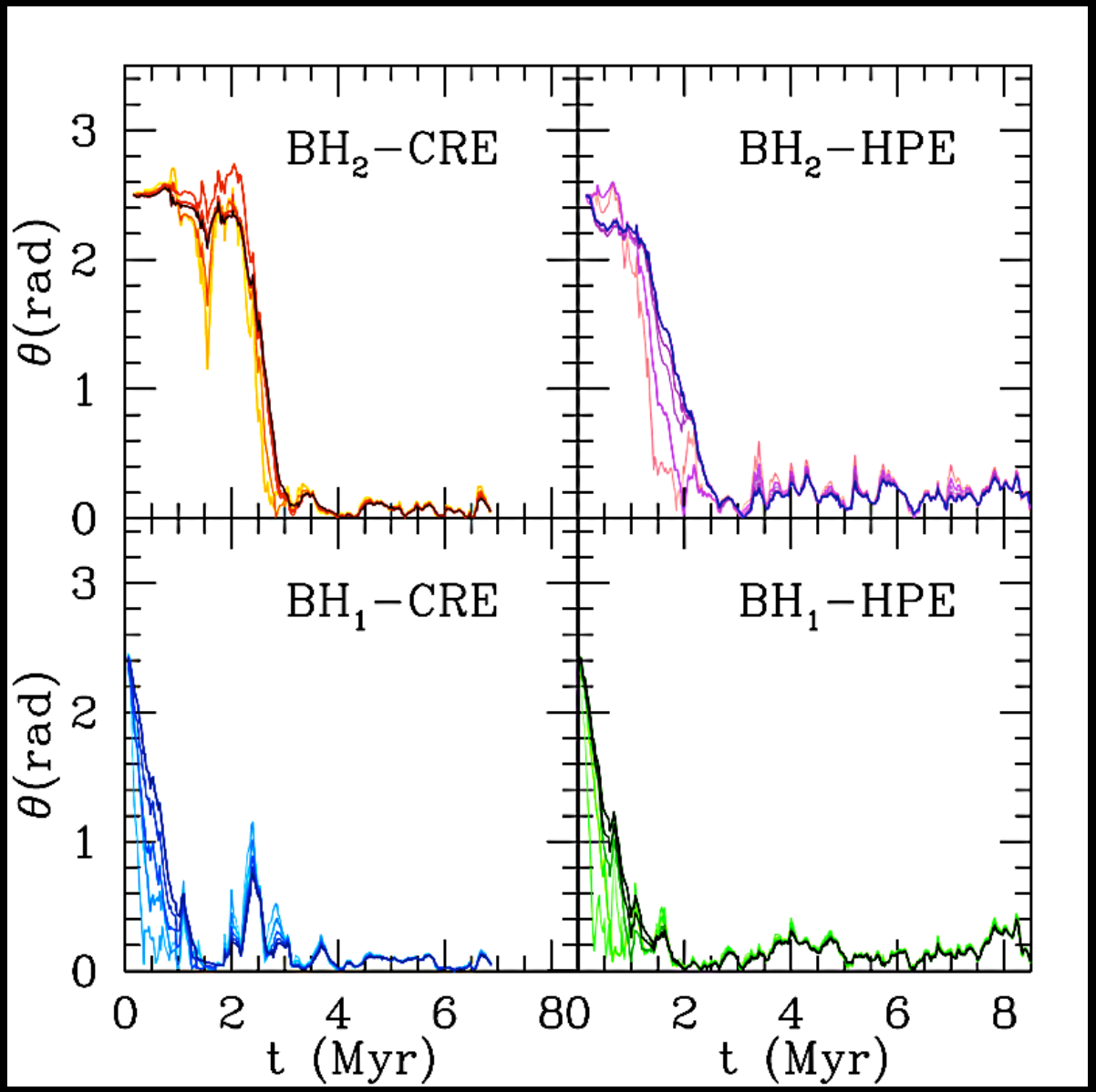
see also
Martin et al 2007;
Lodato & Pringle
2006, 2007

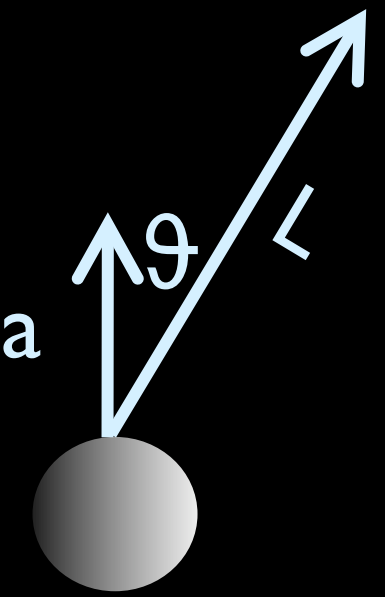






Spin evolution





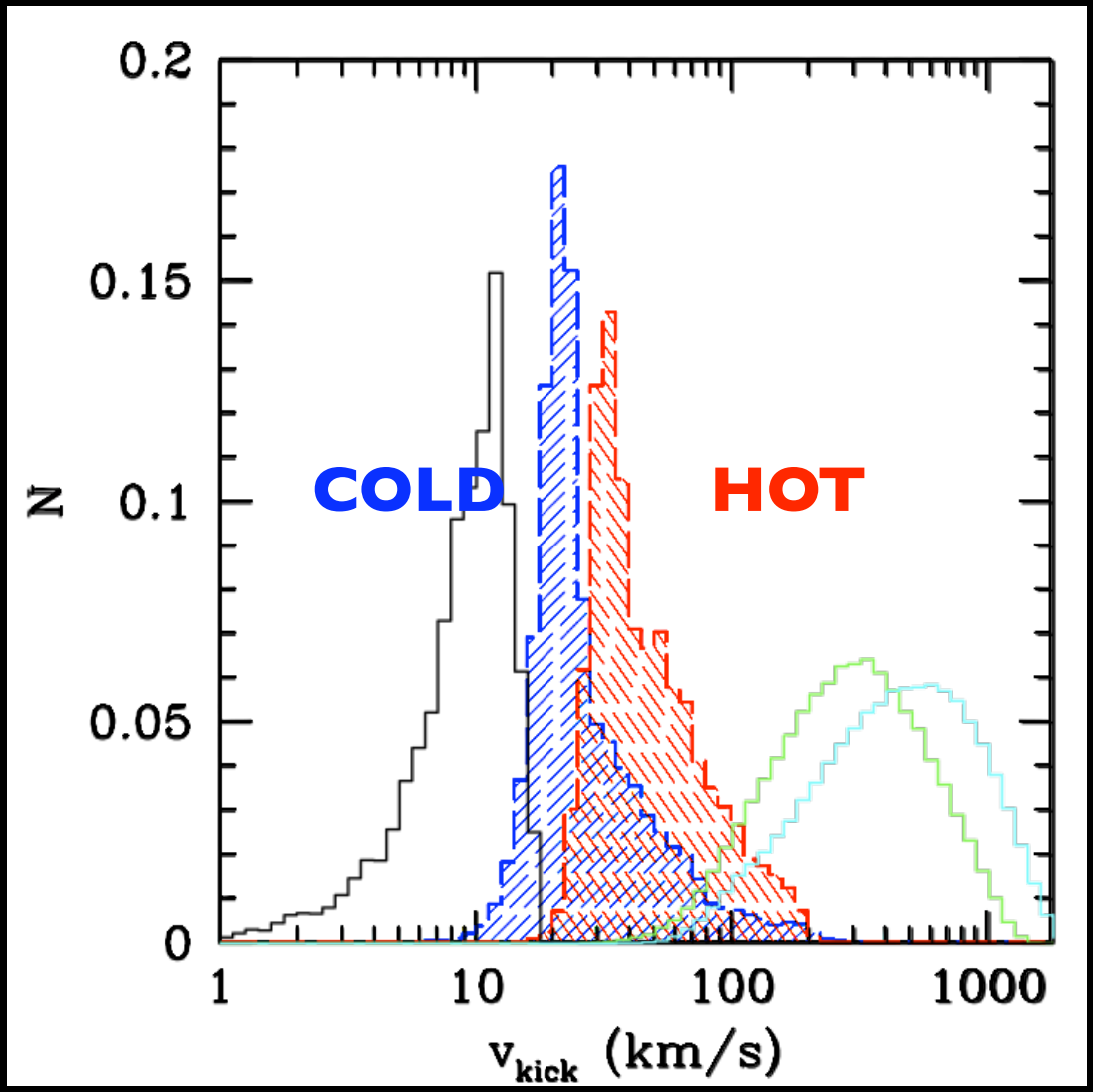
Secondary BH

CRE=cold disc,retrograde orbit
HPE=hot disc, prograde orbit

Primary BH

Gas rich mergers : spins align to orbital angular momentum

Recoiling MBHs



Random distribution of spin moduli

in plane spins

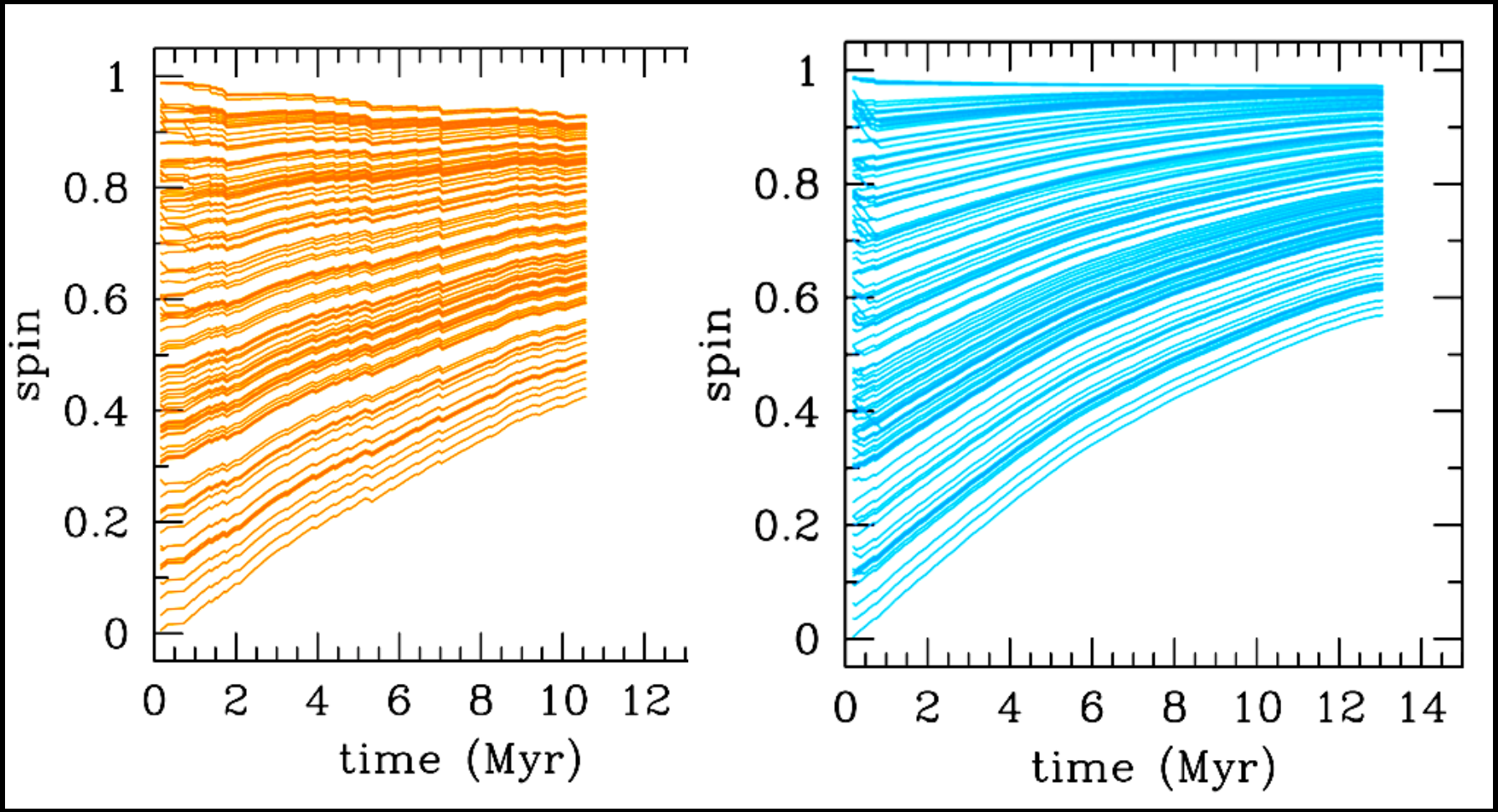
spin-orbit isotropy

aligned spins

Spin evolution: *semi-coherent accretion*

hot disc

cold disc



spins tend toward intermediate-large values

Spin evolution in gas-rich mergers

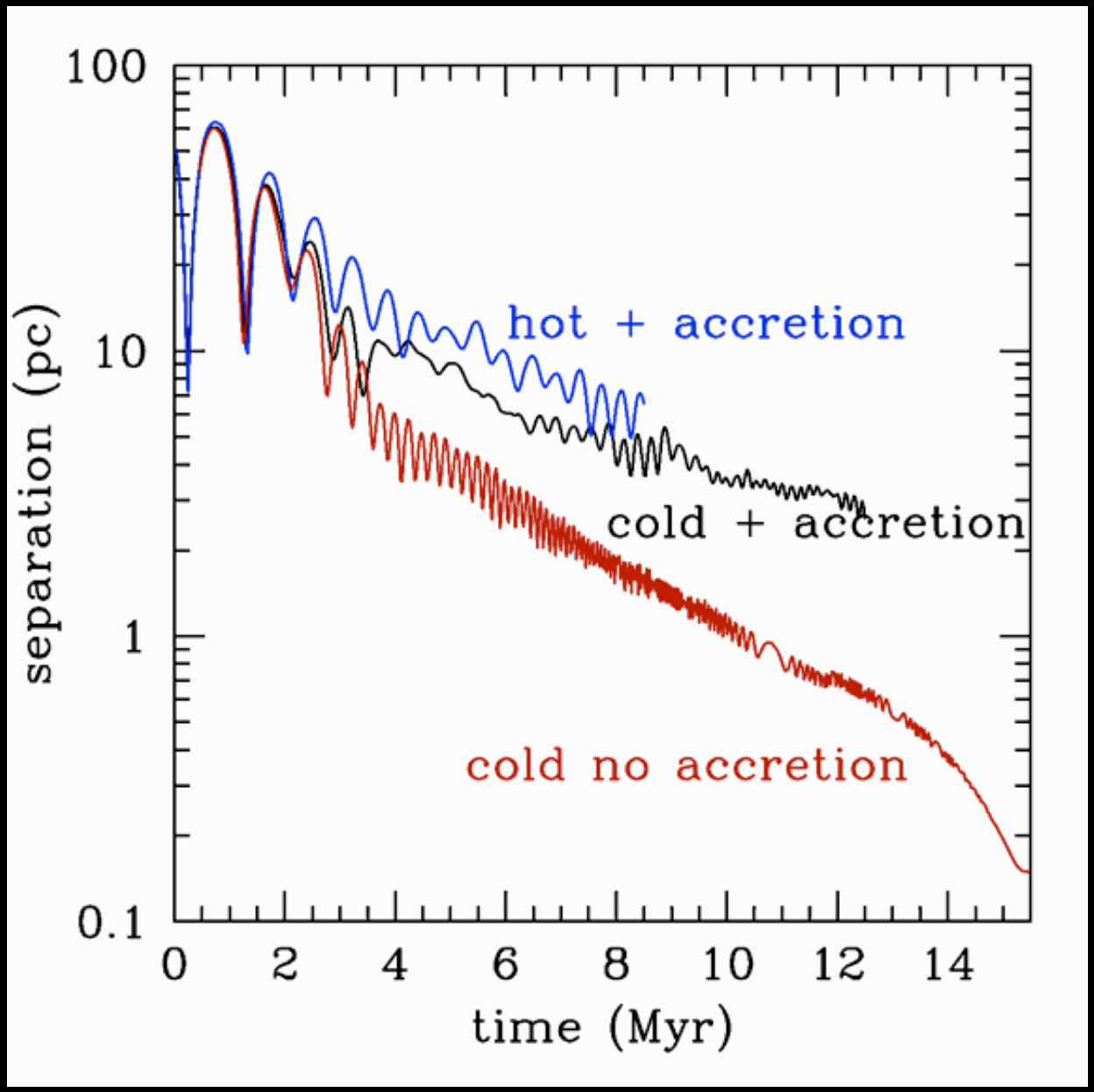
✔ MBH mergers : spins align to orbital angular momentum

✔ MBH accretion: spins tend to intermediate-large values

What we want to know

- How and when BHs accrete mass
- How fast BHs spin
- How and when BHs merge

MBH orbital decay



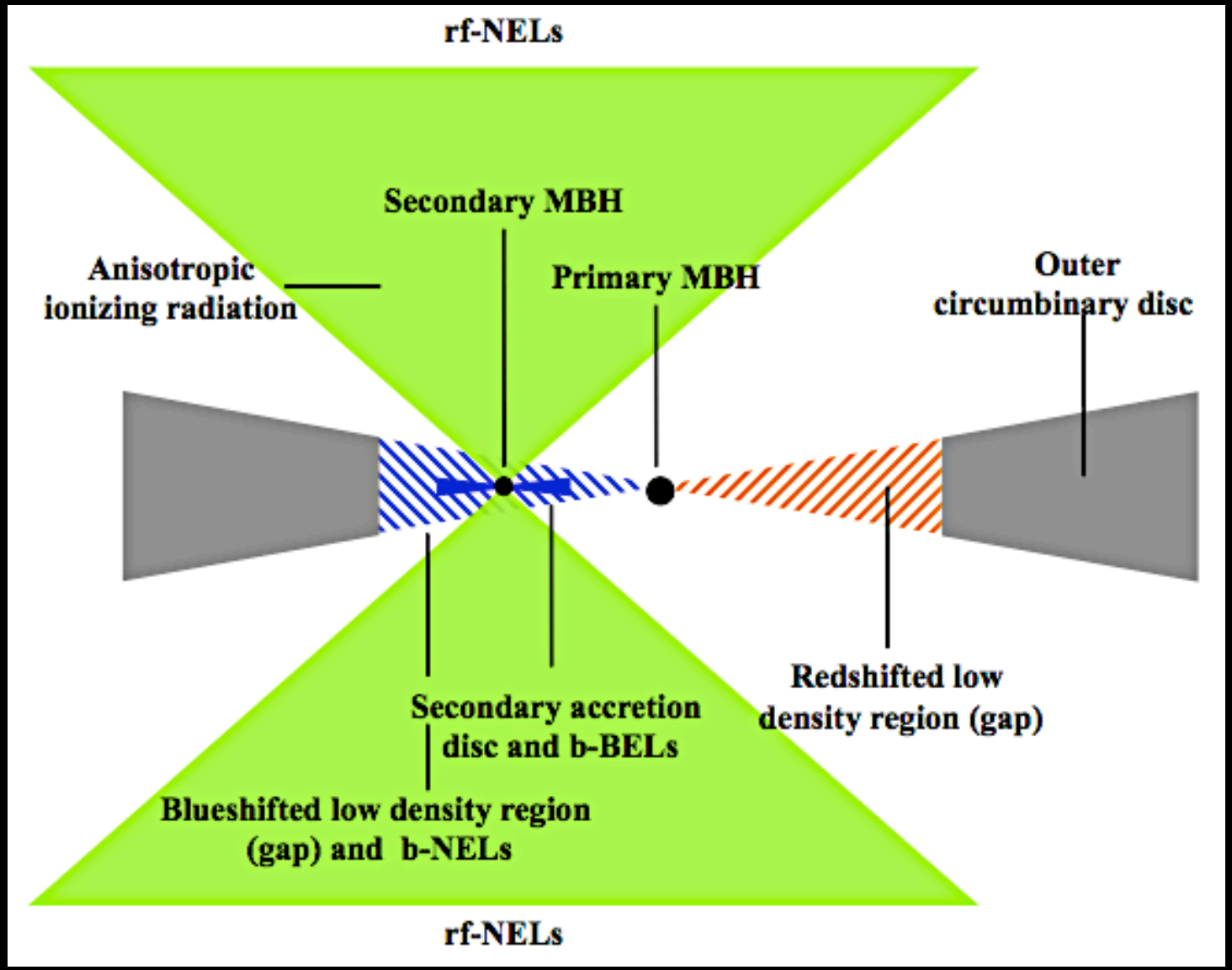
The orbital evolution depends on the **thermodynamical** properties of the gas

The orbital evolution depends on **accretion**

if MBHs swallow gas, the density decreases

Hey, where are all these merging MBHS?

Hunting for sub-parsec binaries



SDSS J092712.65+294344.0
(Bogdanovic et al. 09, Dotti,.., MV et al. 09)

SDSS J153636.22+044127.0
(Boroson & Lauer 09, Chornok et al. 09?)

Sub-parsec binary QSOs

MV, Miller & Dotti 2009

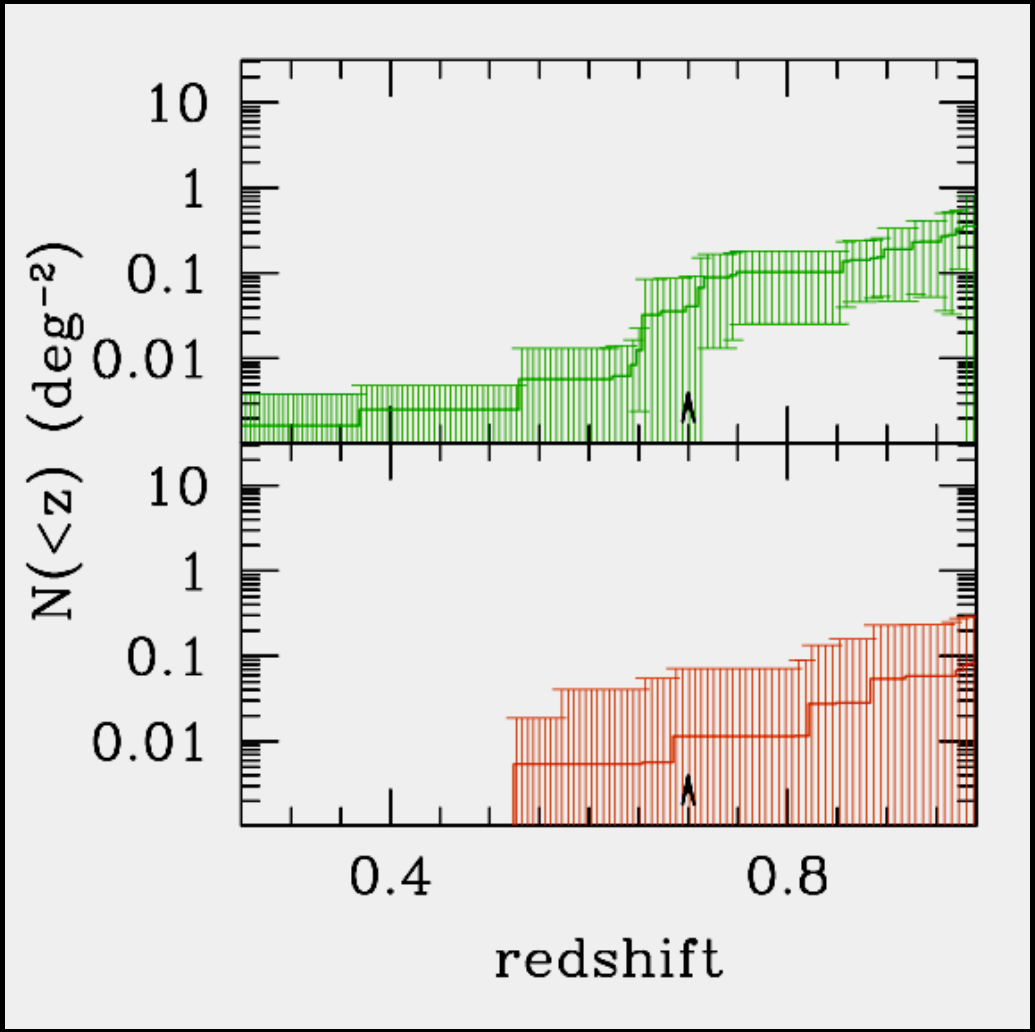
JMM's challenge:

You predict all these tens of mergers per year that LISA will detect.
How come there are so few sub-parsec binary QSOs in the SDSS?!?

- MBH merger rate from hierarchical evolving MBH population
- select only MBHs with v_{orb}>2000 km/s
- assign luminosity
  - all MBHs are active at some level (Merloni 2009)
  - quasars are triggered by galaxy mergers
- assign lifetime

$$t_{\rm life} = 6{\rm Myr}\left(\frac{M_{\rm bin}}{10^7\,{\rm M}_\odot}\right)^{3/4}\left(\frac{4\,q}{1+q^2}\right)^{3/8}\left(\frac{10^\lambda}{0.1}\right)^{-5/8}$$

(Haiman et al. 2009)



All MBHs are active at some level

Merger-driven quasar activity

Most MBH binaries are expected to occur at

- higher redshift
- lower masses

than sampled by the SDSS quasar catalog

MV et al 2003; Sesana, MV & Haardt 2007

Summary

- *accretion*: need to study jointly with *dynamics* and *thermodynamics*
- mergers + accretion: determine *how fast* MBHs spin at merger, and the magnitude of *recoil* velocity
- orbital *decay*: need to study jointly with *thermodynamics* and *accretion*
- merging MBHs are good at *hiding*!